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"STRUCTURE DYNAMICS, VORTEX DYNAMICS AND FLUID LOADING ON STRUCTURES IN WAVES AND CURRENTS"

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14. ABSTRACT The long-term goals of the research have been to investigate the important mechanisms involved in the interaction of current and waves with structures in the ocean. In our studies of tethered spheres or hydroelastic cylinders in a current, we find that they can vibrate with a large amplitude in several different modes of vibration. By employing an analogy to airplane trailing vortices for the sphere VIV, we have been able to predict both the induced force, and the energy transfer responsible for the modes. The cylinder VIV modes are similar to those for bodies with two degrees of freedom, as well as for flexible cantilevers and pivoted cylinders. Perhaps the most significant discovery in this work, is the fact that resonance can extend to infinite flow velocities, if the mass of the structure falls below a special critical value. Our work has formed the basis of comprehensive papers in *Journal of Fluid Mechanics* and several other journals, and has led to an invited review of VIV in *Annual Review of Fluid Mechanics*. The P.I. has founded and chaired a series of international conferences on *Bluff Body Wakes and Vortex-Induced Vibrations* (USA in 1998, France in 2000, Australia in 2002).

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The long-term goals of the research under this award have been to investigate the important mechanisms involved in the interaction of current and waves with structures under the surface, as well as near-surface objects, which are tethered or free to respond to the fluid forcing. We have also undertaken studies which measure in-line and transverse dynamics and forces, wake vortical motions, and signatures of such bodies in current and waves. The support from this award has been used to support a number of students at different periods of their study, and has been instrumental in training them in their PhD programs. The award has been very effective in providing a cohesive research group with sufficient critical mass to move rapidly forward in the research program. The award has been used to support wholly or in part a large number of research publications which are listed at the end of this Final Report.

Our major emphasis with this work has been (and continues to be) the combined study on a number of diverse vortex-induced vibration problems, with a major goal of discovering universal characteristics of such systems. We have completed a large set of studies, some of which are published in *Journal of Fluid Mechanics* and *Journal of Fluids and Structures*, amongst other journals, and are listed in the Publications section later. The support of the Ocean Engineering Area of the Office of Naval Research for both our research, and that of other groups, has directly led to significant steps forward in this field, and the field has progressed far beyond our understanding of one decade ago, mostly encouraged by new techniques in computation and experiment, and also from the study of much lower mass and damping than were hitherto studied. These new results are discussed by the PI comprehensively in an invited review paper, "Vortex-Induced Vibrations" (Williamson & Govardhan, to appear in 2004 volume of *Annual Review of Fluid Mechanics*).

We have been investigating a whole set of different but related problems in vortex-induced vibration, and our goal is to uncover *generic universal phenomena in all these problems of vortex-induced vibration.* We feel that a comprehensive understanding of such *universal* phenomena, which has not been addressed in previous studies to-date, will have a strong impact to the general research field concerned with fluid-structure interactions. We have been studying the following problems comprising vibrating bodies in a fluid flow, noting that Y refers to motion transverse to the fluid flow, while X is parallel to the flow:

- An elastically-mounted cylinder in Y-motion. (Y-cylinder)
- An elastically-mounted cylinder in XY-motion. (XY-cylinder)
- A flexible cantilever in Y-motion.
- A pivoted cylinder in XY-motion.
- A short strumming cable with a standing wave pattern (XY motion).
- A tethered sphere in XY-motion, and also an elastically-mounted sphere in Y-motion.

It should be mentioned that in all of our studies up to this point, we employ the simultaneous measurement of displacement, force and vorticity, and this constitutes the first time such a simultaneous approach has been used in free vibrations (see Khalak & Williamson, 1997;1999; Govardhan & Williamson, 2000). We have been using extensively the Cornell-ONR Water Channel, for the primary experiments involving flow-induced vibrations. We have also been using the computer-controlled X-Y Towing Tank for detailed visualisation and force measurements for bodies in steady/unsteady motion. We have also employed two of our Wind tunnels to extend some of our tethered body work.

We have made substantial progress on these projects funded by the ONR, leading to some new discoveries, and to a large number of refereed journal publications (please see Publications List). Recent discoveries have been made in vortex-induced vibration studies concerned with an elastically-mounted cylinder, and with a tethered sphere, (Khalak & Williamson, 1996, 1997, 1999; Govardhan & Williamson, 1996, 1999, 2000, 2001). In the former case, we have a system which restrains the cylinder to move only transversely to a free stream (in Y-motion only), with the cylinder riding beneath an air-bearing system held over the Cornell-ONR Water Channel flow. In the latter case, we have a sphere which is tethered by a thin cable, positioned in a fluid flow, and it is therefore free to move predominantly in a horizontal plane in 2 degrees-of-freedom (sphere in XY-motion). We have also mounted the sphere on a sting, enabling it to be attached to the air-bearing system, and to allow translation only transverse to the flow (sphere in Y-motion). These sphere VIV studies are comprehensively to be reported in Govardhan & Williamson (2003, *Journal of Fluid Mechanics*), and in Jauvtis & Williamson, *Journal of Fluids and Structures* (2001, 2003); Jauvtis & Williamson, *Journal of Fluid Mechanics (2003)*.

In our study of a hydroelastic cylinder, we have utilised an arrangement, which, like the above sphere problem, has minimal intrusion. We have been able to measure forces simultaneous with the cylinder displacements, using the tailor-made force balance. We set up a hydrogen-bubble visualisation technique, which has been used in a qualitative manner to infer basic vortex motions. Digital Particle Image Velocimetry is used to determine the vortex dynamics. We have discovered the existence of four regions of amplitude response, as the normalised velocity is increased through "resonance". The regions may be defined as the *initial excitation regime*; the *upper branch*; the *lower branch*; and the region of decoherence. Hysteresis and intermittent-mode-switching have been demonstrated, as the flow transitions between these regimes above. These mode switches are dependent on the mass ratio and damping, amongst other parameters. Force measurements have been measured extensively with the position data. Very large Lift coefficients of 4.5, and drag coefficients of 6.0, have been measured within the regions of excitation. Perhaps the largest effect of body vibrations on the induced forces, is for the fluctuating drag, which can reach 60% of the mean drag, which is 150 times that found for the static cylinder.

One of the new contributions of our studies would appear to be the understanding that there are two distinct types of response of a VIV system, depending on the level of the normalised mass-damping parameter ($m^*\zeta$). For a cylinder in Y-motion with a high-($m^*\zeta$), we find a classical 2-Mode type of response, consistent with the classical work of Feng (1968). However, by taking the mass-damping to extremely low levels, we have discovered the presence of a 3-Mode type of response, where there exist 3 branches of amplitude, namely the Initial, Upper and Lower branches. Other investigators initially assumed that our 3-mode results (Khalak & Williamson, 1996) were the result of a problem with resolution, which is an understandable interpretation, although our work further confirms the distinct modes by demonstrating that there exist discontinuous jumps between the modes. Our vorticity plots have shown that the initial branch is associated with the 2S mode of vortex formation, while the Upper branch corresponds with a different pattern, namely the 2P mode. The 2S mode comprises 2 single vortices being formed per cycle of vibration, while the 2P mode is one where there are two vortex pairs formed per cycle. The existence of these two quite distinct vortex modes is consistent also with the hysteresis found between these response branches. The lower branch of response corresponds also with a 2P mode.

The fact that there is a jump in classical phase Φ (between the lift force and the displacement) at the second jump, i.e. between Upper <--> Lower branches of amplitude response, is contrary to the assumptions made in Zdravkovich (1982), and widely accepted since that time, that such a jump is consistent with a switch in timing of vortex shedding. In our low-($m^*\zeta$) case, *the switch in vortex shedding timing does not occur when this phase Φ jumps,* since the vortex mode remains as the 2P mode for both branches. The switch in vortex timing occurs only when the vortex mode changes from 2S to 2P, at the jump between the Initial <--> Upper branch, as one might expect. If there is a vortex mode jump between Initial <--> Upper branch, then we deduced that there must be a quantity that *does indeed jump* across this discontinuity. We therefore introduced in Govardhan & Williamson (2000)

the concept of a *vortex phase*, as opposed to the classical (and what we define here as the) *total phase*. The vortex phase is the phase between the vortex force (only) and the displacement, and will be influenced by vorticity dynamics only. The total phase is between the total force and the displacement. If there is a jump in vortex mode then surely there will be a jump in vortex phase, and indeed this is what is found.

TOTAL PHASE   = Φ_{TOTAL} = Phase between TOTAL force - displacement (classical definition).

VORTEX PHASE   = Φ_{VORTEX} = Phase between VORTEX force - displacement.

In order to use this concept, we had to formulate two distinct equations of motion, as follows below. The classical equation of motion, involves the total fluid force (vortex force plus potential force) on the right hand side, and the total phase Φ_{TOTAL}:

Equation of motion using "Total force":

$$m\ddot{y} + c\dot{y} + ky = F_{TOTAL} \sin(\omega t + \phi_{TOTAL})$$

and so the relevant natural frequency for this equation of motion is $f_{N\ VACUUM}$. The alternative equation of motion, involves the vortex force (only) on the right hand side (so the added mass term shows up on the left side of the equation), and here we introduce the vortex phase Φ_{VORTEX}:

Equation of motion using "Vortex force":

$$(m + m_A)\ddot{y} + c\dot{y} + ky = F_{VORTEX} \sin(\omega t + \phi_{VORTEX})$$

and so the relevant natural frequency for this equation of motion is $f_{N\ WATER}$.

We should now point out that our 3-Mode response corresponds to what one might expect: the first mode jump involves a vortex mode change, and correspondingly a jump in vortex phase Φ_{VORTEX}, and occurs when the frequency of oscillation (f) passes through $f_{N\ WATER}$; the second mode jump occurs when there is *not* a vortex mode change but nevertheless there is a jump in total phase Φ_{TOTAL}, at which point we find the oscillation frequency passes through $f_{N\ VACUUM}$. These two equations and our introduction of the concept of two distinct phases, now explains the existence of a 3-Mode response that we first discovered in Khalak & Williamson (1996).

The fact that, for high mass-damping (m*ζ), or simply high mass (m*), the switch in timing of vortex shedding does indeed coincide with the jump in classical (total) phase Φ_{TOTAL}, is consistent with the fact the natural frequencies $f_{N\ WATER}$ and $f_{N\ VACUUM}$ become almost coincident, the Upper branch is squeezed out of existence between the Initial and Lower branches, and the vortex mode jumps clean across from the Initial to Lower branches, and one finds the classical 2-Mode response of Feng (1968)!

In the case of the sphere VIV system, the wake vorticity concentrations are found to be vortex loops and vortex rings, instead of the rectilinear vortices, which are found for the cylinder wake. Vortex wake modes defined as 2S and 2R modes have been found for the sphere, which are beautifully analogous to the 2S and 2P modes for the cylinder (such modes were discovered and described originally in Williamson & Roshko, 1988). Similarities between vortex formation modes in these very different flows, have been shown from vorticity measurements, where the cylinder exhibits the classical 2P mode, comprising 2 vortex *Pairs* per cycle of oscillation, while the analogous sphere wake is the 3D counterpart, namely the 2R mode, comprising 2 vortex *Rings* per cycle. In addition, and still an exciting unexplained phenomenon, is the existence of a large-amplitude periodic "Mode III" at much larger normalised velocities, and only found for the sphere case. This mode is clearly radically different from the classical 2S and 2P modes found for the cylinder, and is not the result of a synchronisation of 2 or 4 vortices per cycle, but involves large numbers of vortices per cycle, whose dynamics nevertheless are

capable of energy transfer to body motion. In all the modes I, II and III for the sphere, the vibrations can be closely periodic, and at a large amplitude of around one diameter, for conditions of low mass-damping. A further analogous result (out of a number of such results) to mention briefly is (what we define as) the "Griffin plot" for a freely vibrating sphere, where the amplitude is plotted versus the mass-damping parameter [after Griffin (1980) who originally plotted such data for a cylinder], and bears a strong resemblance to such plots for the vibrating cylinder.

Similarities between the sphere and the cylinder dynamics suggested to us that there might exist universal or generic body dynamics and vortex formation modes, in all of these diverse VIV problems.

If we restrict, for the moment, our discussion to only one aspect of these problems, namely typical response plots for various different VIV systems, one can see immediately the similarity in the types of response branches to be found for cylinders in one or two degrees of freedom, and the cases of flexible cantilevers and pivoted cylinders. Of course there are many other corresponding features, besides the form of the response plots, and we have been led to study the universal characteristics between such diverse VIV systems, and why such universal features should exist. This is an ongoing research program.

Returning to the case of the tethered sphere, or elastically-mounted sphere, these results indicate a number of similar characteristics with the cylinder VIV problems, although the mechanism by which the dominant vortex dynamics yield energy transfer into body motion, are distinctly different. Although we have written several papers on sphere VIV under this award, the most recent one being prepared for *Journal of Fluid Mechanics* is the most comprehensive, and contains DPIV images of the vortex dynamics downstream of the vibrating sphere,. A principal feature is that the dominant vorticity is arranged streamwise to the flow - *the wake comprises essentially a series of streamwise vortex loops.* How do these loops yield transverse body dynamics ? Our approach to this was to think about an "airplane wake analogy". An airplane, whose principal wake is in the form of a trailing vortex pair, has an amount of lift force on the wings (and body) which is equal and opposite to the rate of change of vorticity impulse in the vertical direction (force = rate of change of momentum), and so one can write the equation:

$$\text{Lift} = \rho \, U \, \Gamma \, b$$

where ρ is the fluid density, U is the speed of the aircraft, Γ is the "tip" vortex strength, and b is the distance between these tip vortices. One can simply turn this idea "on its side" and interpret the transverse force on a vibrating sphere as being the result of the rate of change of the horizontal vorticity impulse due to the streamwise vortex loops, analysed in a quasi-steady sense. By actually measuring such streamwise vorticity generated by the body, as a function of time, we have found a surprising agreement between the directly measured transverse force and the force inferred from the airplane wake analogy, thus suggesting that almost all the (vortex) force and energy transfer leading to the sphere dynamics comes from these streamwise "trailing" vortices. This is a major new result coming from the sphere VIV study.

In the case of the XY-cylinder (a cylinder with two degrees of freedom, both streamwise (X) and transverse (Y) to the flow) we thought early in our previous studies that the ability of the body to move streamwise as well as transverse to the flow, had only a small effect on the transverse vibration response (Jauvtis & Williamson, 2002), but we later discovered that if one reduces the mass ratio below about m*=6, then the dynamics change dramatically. A very large response amplitude appears, which is remarkably periodic, and which is induced by a distinct new vortex formation mode, known as the "2T" mode. This mode comprises 2 "triplets" of vortices formed per half cycle, using the terminology of Williamson & Roshko (1988). Simple, but key, analysis shows that it is the third vortex per half cycle that yields the energy transfer sufficient to generate the surprisingly large amplitudes up to 1.5 diameters.

We have also studied different cases where cylindrical structures have a variation of response amplitude along their span. We have investigated the case of a flexible cantilever in conjunction with a

group under Celso Pesce at University of Sao Paulo (Brazil), Fujarra et al., (2001), and have found remarkably similar response modes that are found for the Y-cylinder case. A fruitful study ensued from research into the dynamics of a pivoted cylinder, which is to be submitted soon to *Journal of Fluid Mechanics*, Flemming & Williamson (2003). All of these results are expected to have relevance to the case of a flexible cable under vortex-induced vibration. The pivoted cylinder is quite fundamental, because it involves the simple case of a linear variation of amplitude, although the vortex formation dynamics and the structural dynamics are quite complex and fascinating. We have discovered several modes of vortex formation, two of which are mentioned here, yielding large vibration amplitudes. One vortex wake mode is analogous to the 2S-2P Hybrid mode found by Techet et al. (1997) in their case of a vibrating tapered cylinder. Essentially one finds a 2S mode (2 single vortices per cycle) over part of the span, coexisting (by the mechanism of vortex dislocations) with the 2P mode (2 vortex pairs per cycle) over the remaining part of the cylinder span. A further mode has been found comprising 2 co-rotating vortex pairs being formed per cycle, or a "2C" mode, which yields very large tip responses of around 1.5 diameters. In this case one must include a third dimension (the streamwise amplitude), which shows that the 2C mode is associated with significant streamwise motion, in similarity with the 2T mode for the XY-cylinder. In essence, our studies indicate that, among the several possible vortex modes, only the following modes yield positive energy of excitation leading to body dynamics, and only these have been found in vortex-induced vibration studies to date:

$$\{ \text{2S, 2P, 2T, 2C} \}$$

We shall mention a central result that has a strong bearing on our quest for generic phenomena pertaining to a whole class of VIV systems. The result in question is our discovery of the existence of a CRITICAL MASS for a body undergoing vortex-induced vibration (Govardhan & Williamson (2000, 2002). In the case of a cylinder, the critical mass is given by the mass ratio:

$$Critical\ mass\ ratio\ =\ m^*_{CRIT}\ =\ 0.54.$$

and is valid for small values of mass-damping. We feel that the significance of this new result is far-reaching. If the mass of the oscillating body falls below this critical value, then the large-amplitude resonant oscillations of the system will persist up to infinite flow velocity. *In other words, the body never falls out of resonance, no matter how high the free stream velocity is increased.* The extent of the synchronisation regime (as measured by a range of normalised velocity U* for large-amplitude response) extends to infinite U* when the mass approaches 0.54 (Govardhan & Williamson, 2000). By removing the spring restraint for the transverse motion of the cylinder VIV system (Govardhan & Williamson, 2002), we were able to take the normalised velocity right to infinity, U* = INFINITY, and prove that as one reduces (very carefully indeed) the mass of the structure (on air bearings) then the body suddenly generates vigorous large-amplitude motion at a critical mass of 0.542, agreeing remarkably well with the previous predictions from quite independent experiments!

Despite the rather simple nature of this new and surprising result, it would appear to have significant practical applications. It is further found, in our separate study of the dynamics of a tethered or elastically-mounted sphere (Govardhan & Williamson, to be submitted to *Journal of Fluid Mechanics*, 2003), that the critical mass in that case is m^*_{CRIT} = 0.30. These ideas are radically different from the classical view of fluid-structure synchronisation as being restricted to a velocity such that the oscillation frequency is close to the natural structural frequency. One must ask the question: *Does a critical mass exist for a whole class of VIV systems ?* This is one of the questions we have previously addressed in our research, and we shall continue to study, although the simple deductions in Govardhan & Williamson (2002) suggest that a critical mass must necessarily exist for all VIV systems.

Most of the results of our research have been included in several publications which have been placed in the List of Publications. Invited presentations and conference seminars have been presented, and the PI has been Co-Chairman (and founder) of a series of conferences bringing together many of the world's leading researchers in this field of research; to Washington, D.C., for the *Conference on Bluff Body Wakes and Vortex-Induced Vibrations* (3 days - 67 seminars), *BBVIV-1* (1998); to Marseille, France, *BBVIV-2* (2000); and to Port Douglas, Australia, *BBVIV-3* (2002). Support in the

publication of the Proceedings Volumes came from ONR. It is certainly true that much of the recent impetus over the last decade in this field has arisen due to the support from ONR.

Our work has been presented at several major conferences, and has formed the basis of papers in *Journal of Fluids and Structures, Journal of Fluid Mechanics* as well as *J. Wind Engineering and Industrial Aerodynamics*, as well as our invited review paper in *Annual Review of Fluid Mechanics.*

These fundamental studies of fluid-structure interaction have direct application to the structural dynamics, and corresponding vortical wakes of cylindrical structures and tethered bodies, under or near the free surface. Our investigations of the tethered-body problem show that proper account of the unsteady dynamics of such tethered structures are very important to a correct prediction of the wakes and signatures. The work here shows that over a wide range of experimental conditions, the tethered sphere oscillates vigorously, yielding 100% magnification factors on the induced drag and tether angle. An important practical implication is given by the very large range of normalised velocity over which synchronised self-excited motions are found. It is also important to understand typical induced frequencies in these problems.

We have set up a vortex-induced vibration experiments involving an elastically-mounted cylinder, with extremely low mass and damping, as well as several other problems, including bodies in two degrees of freedom, flexible cantilevers, and pivoted cylinders. The frequency response at low mass-damping, and the form of the amplitude response, as a function of incident flow velocity, has applications to vortex-induced vibrations of structures in a current. The question as to how much a structure will move, given the structural parameters, is perhaps the most basic and practical question one might pose, and though a simple question, the dynamics are subtle and rich in phenomena. The question as to how much force is exerted (very large lift and drag coefficients of at least 4.5 - 6.0, for example) is also a most basic practical question to vibrating structures.

These apparently simple, yet significant, fundamental questions, which have distinct practical application, provide a strong driving force in our work.

PUBLICATIONS

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C. H. K. Williamson (2004) "Vortex-Induced Vibration", First draft submitted (April 2003) to *Annual Review of Fluid Mechanics*, **36**.

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